Cost Effective Assessment of System Reliability Using Data from Subsystem/Assembly Level Testing

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Abstract

The paper describes a simple method developed to use and combine subsystem or assembly level accelerated test results with the system level test results to estimate achieved overall system reliability.

The time schedules for product delivery usually do not allow adequate test duration for system reliability assessment or demonstration with a desirable degree of confidence. Also, the complexity of failure isolation and diagnosis at the system level, along with the implementation of corrective action can be an additional cause of undesirable delays and schedule slips. With the assembly and subsystem level accelerated testing and reliability assessment, a special attention can be devoted to those assemblies/subsystems identified 10 need additional test time and the reliability and quality improvement. Testing at the integrated system level can then address system level problems usually caused by integration or interaction of the subsystems, as well as to the interface problems.

To reduce the test duration, test acceleration is usually applied. In addition 10 the limited available system test time, there is the issue of appropriate test acceleration for a system. This issue can become very important in case of complex systems. Different subsystems or assemblies usually have different critical failure modes and different failure mechanisms. The proper type of test acceleration applied is the one that is related to the specific failure mechanism, i. e. thermal, electrical, dynamic, etc. Adequate test acceleration can be determined with more accuracy for assemblies of smaller size to minimize over-s[rcss or under-stress of individual components or groups of components.

Key Words

Achieved reliability, goal reliability, assembly level test time, system level test time, test acceleration, subsystem reliability, system reliability.

1.0 introduction

The need for an improved, yet time efficient method of assessing system reliability is based on the recognition that one of the major constraints of most programs is the length of time allowed for reliability assurance testing of the completed/assembled system. In addition to the usually frantic delivery schedules, launch date deadlines, a very important factor, cost of testing, cannot be neglected when having in mind the limited funds of the fixed price contracts. Rather than for extensive duration of operational and reliability testing the resources can be devoted 10 the higher technology development.

The method of combining the assembly, subsystem, and system level test results allows assessment of the system reliability with considerable cost and time saving.

For reliability demonstration, usually through reliability improvement/growth testing, the available test time is usually not sufficient. Thus the test acceleration becomes a very important and required factor when planning the test program. Different assemblies have different predominant failure mechanisms and different acceleration factors, therefore, there is not one kind of test acceleration that can be applied to the integrated spacecraft system. The need for testing of assemblies or at the most subsystems separately then becomes obvious. Separate testing of assemblies and/or subsystems then points to a need to evaluate the results and combine information with

When a test acceleration is required, the most frequently encountered stumbling point has always been the means of test acceleration. In many cases in industry and literature test acceleration was done by increase in test ambient temperature. This method, relatively adequate when the primary failure mechanism is thermal stress, obviously is not universal, and other acceleration methods must be applied dependent on failure mechanisms. Also, even when the thermal stress is the primary failure cause, is very hard to estimate a common activation energy for all components in a system. Approximation may lead in considerable errors in determination of the test duration, as some components would be over-stressed, while others may be under-tested. Breaking up the system in subsystems and assemblies if not offering a solution, may to some degree reduce the acceleration problems.

The method presented in this paper, although based on well known and established reliability testing techniques, offers a means for more accurate test acceleration that accounts for changing failure rates, as well as the method for assessment of system reliability based on subsystems test data.

2.0 Test Acceleration

Test acceleration depends on the failure mode-failure distribution models, and for complex systems is very difficult to obtain. To simplify test duration calculations, it is often practiced to address a limited number of predominant failure modes and thus address a relatively simple multivariate relationship. Reference 1 gives an extensive explanation of various acceleration models. Since the two basic methods for reliability growth assume constant failure rate within a test interval, that is, the Poisson Process, the test acceleration is based on multiple failure modes - Exponential distribution (non-homogeneous Poisson distribution). In an idealized example where the thermal failure mode is predominant for an assembly, and the component activation energies are similar and can be assumed equal, the Arrhenius test acceleration in reliability growth process can be written for the two models:

Table I. Thermal Acceleration in Reliability Growth

Duane Model	$\frac{t_2}{t_1} = \left\{\exp\left[-\frac{E}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right]\right\}^{\frac{1}{1-\alpha}}$
AMSAA Model	$\frac{t_2}{t_1} = \left\{\exp\left[-\frac{E}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right]\right\}^{\frac{1}{\beta}}$

Where:

t_2 = accelerated test duration

t_1 = initially calculated test duration

E = activation energy (eV)

k = Boltzman's constant = 8.62E-5 eV/K

T_1 = normal test temperature

T_2 = elevated test temperature.

Similarly the power-exponential relationship, when the power applied (V) is a factor influencing the characteristic life, is expressed as:

$$\lambda(V) = e^{-a}V^{b}$$

Where the assumed constant failure rate is a function of applied power, and a and b are constant dependent on component (a) and the test method (b).

Table II. Power Acceleration in Reliability Growth

Duane Model	$\frac{t_2}{t_1} = \left(\frac{V_1}{V_2}\right)^{\frac{b}{1-\alpha}}$
AMSAA Model	$\frac{t_2}{t_1} = \left(\frac{V_1}{V_2}\right)^{\frac{b}{\beta}}$

Where:
V_1 and V_2 = normal and accelerated (increased) power stress, respectively.

It is apparent that it is not desirable to increase any of the stresses considerably during the reliability growth testing, as this type of tests assumes replication of the mission environment. Moderate increase in appropriate stress will, however result in considerable test lime saving.

With the help of a thorough circuit analysis, it is possible 10 adjust the appropriate stresses in such a way that the test acceleration is the same for the majority of the crucial components. This simplifies the test operations and the resultant reliability calculations.

3,0 Minimum Operational Test Duration

The operational test duration was calculated for a spacecraft, however, all assumptions can bc applied in its original form or modified to any other device under reliability growth lest,

3.1 Assumptions

Mission duration: Approximately 3 years. The mission duration does not affect the duration of the test time, as the mission reliability is provided for by the design.

S/C design and construction: Similar to Earth Orbiter S/C

Reliability improvement: Per the rule which is widely accepted in industry for newly developed or for newly produced item, it is assumed that the beginning failure rate is equal to ten times the desired mission failure rate at the time of launch.

Test Failure Correction: Aggressive, and if possible industry recommended average reliability growth rate of α = ().5. Implies well organize.(i anti intensive Failure Reporting and Corrective Action System.

Test failure modes: Design, Workmanship, and Random failures

S/C Configuration: Cross-strapped at the subsystem level

Scored failures: Critical at the subsystem level. One failure fatal to the subsystem
Component "Random" Failures: Corrected by part improvement (higher quality part, higher rated part), or design improvement. Replacement of the failed part with a new, identical part dots not guarantee that the replacement part will not also fail within the short time period.
Multiple Induced Failures: Only the first, originating failure is scored. Correction of the original failure corrects the problem,

Spacecraft Failure Rate: The spacecraft failure rate was determined to decr case for electronic assembl its, and is relatively constant for the mechanical assemblies that are a part of propulsion system. In previous study it was determined that the spacecraft electronics failure rate follows Weibull distribution. This failure rate app] ics 10 the spacecraft and spacecraft assembl ics when configuration is such that all components arc in series. A reliability model is derived in the past years to apply MIL-HDBK-217-predicted constant failure rate, anti to obtain realistic reliability predictions.

An example of applications of the new model is in Figure 1.

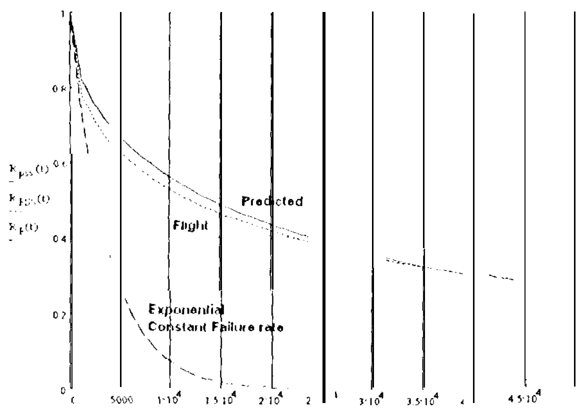

Figure 1 Single String Magellan Predicted Reliability vs. Flight Experience.
Assumed Shape Parameter β = 0. 5

3.2 Design and "Random" Failures

The title of this section implied design improvement even in the case of a part failure (use of a better m higher rated part, change in design),

Spacecraft electronics reliability is:

$$R_E(T_M) = \left(\exp\left(-w\cdot\lambda\cdot T_M^{\beta}\right)^4 + \exp\left(-w\cdot\lambda\cdot T_M^{\beta}\right)^4 - \exp\left(-w\cdot\lambda\cdot T_M^{\beta}\right)^4\cdot\exp\left(-w\cdot\lambda\cdot T_M^{\beta}\right)^4\right)$$

Spacecraft propulsion reliability is:

$$\left(2\cdot\exp\left(-\lambda_P\cdot T_M\right) - \exp\left(-\lambda_P\cdot T_M\right)^2\right) = R_P(T_M)$$

Where:

λ = MIL-HDBK-217-predicted failure rate for electronics,
λ_P = MIL-HDBK-217-predicted failure rate for propulsion,
T_M - mission duration
β = shape parameter of the new spacecraft

$$w = \left(\frac{1}{\lambda_0\cdot\eta_0^{\beta_0}}\right)^{\frac{\beta-1}{\beta_0-1}}$$

λ_0 = MIL-HDBK-217-Predicted failure rate for a reference, known, spacecraft
η_0 = Characteristic life of the reference S/C
β_0 = Weibull shape Parameter of the reference spacecraft.

The Weibull decrease in failure rate is not pronounced during test time, as the test time is relatively short when compared with the mission time. For this reason, the natural decrease in the spacecraft failure rate will be neglected in the rationale for the test duration.

The goal of the accelerated test is to achieve the average failure rate that the spacecraft must have in the beginning, of flight if it is to achieve the desired mission reliability. This beginning average failure rate is:

$$AFR_1 = \frac{1}{\eta^{\beta}}$$

p. 1

$$AFR_1 = \left(\frac{1}{\lambda_0\cdot\eta_0^{\beta_0}}\right)^{\beta_0^{-1}}\cdot\lambda$$

If used Duane reliability growth model, the goal mean time between failures must be equal to the reciprocal of the AFR_1

$$\theta_P = \frac{1}{AFR_1}$$

The reliability growth test duration is then calculated as:

$$T_T = \exp\left[\frac{\ln\left[\frac{-(1+\alpha)}{AFR}\right],\ \ln\left[\frac{1}{(10\cdot AFR_1)}\right] + \alpha\cdot\ln(T_1)}{\alpha}\right]$$

where:
α = growth rate,
T_1 = time of the beginning of test
T_T = test time duration, non-accelerated for the design failures (originally "random").

For the propulsion subsystem, the test duration is found from:

$$T_P = \exp\left[\frac{\ln\left[\frac{-(1+\alpha)}{\lambda_P}\right] - \ln\left[\frac{1}{(10\cdot\lambda_P)}\right] + \alpha\cdot\ln(T_1)}{\alpha}\right]$$

3.3 Workmanship Failures

As there are normally 10 subsystems in a redundant spacecraft with a minimum of 5 operational subsystems, the maximum number of failures that could be tolerated is r = 5.

Assuming that the workmanship failures are Poisson-distributed, the spacecraft failure rate regarding workmanship failures is calculated from:

$$P(x>5) = 1 - \sum_{i=0}^{5}\frac{(\lambda_W\cdot T_M)^i}{i!}\cdot\exp(-\lambda_W\cdot T_M)$$

If probability of occurrence of five failures is set low, the spacecraft "constant" failure rate regarding the workmanship failures is calculated from:

$$P(\lambda_W) = 0.084$$

$$\lambda_W = 1.142\cdot 10^{-4}$$

The ratio of probability of occurrence and the workmanship failure rate is shown in Figure 2.

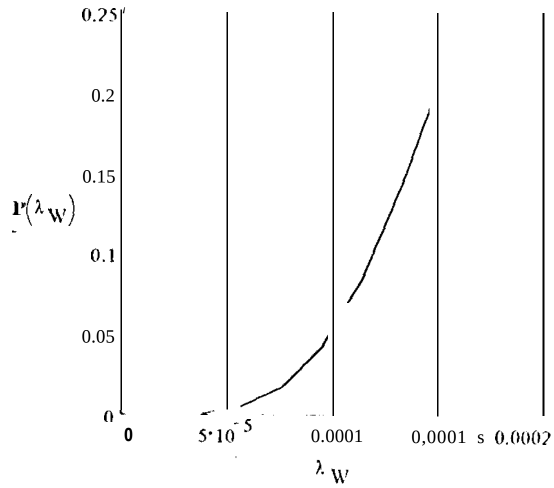

Figure 2. . Probability of maximum workmanship failure occurrence as a function of the failure rate.

4.0 Calculated Test Duration

The test duration is calculated based on the assumption that the desired reliability improvement through elimination of design and workmanship problems is such that the final reliability (time to a possible failure) is ten times the time to a failure at the beginning of test. This approach has been widely used in the Industry during the past J O years and has the following meaning:

- Requited reliability of the product is provided by the design (fault protection, redundancy, part quality, derating, etc.). The designed reliability, however, is normally compromised by the unnoticed design errors (choice of parts, unpredicted stress, or other causes), compatibility errors, and workmanship, or manufacturing process errors. As widely experienced by the industry, when the product is not a totally new design, and when the quality of the design and manufacturing processes is high, the new product failure rate will be approximately ten limes the designed or desired failure rate. This means that the time 10 a critical failure at the beginning of test of a newly manufactured product will approximately be ten times shorter than the desired time to a critical failure.

The calculated test duration with the appropriate test acceleration is given in Table III,

Table] 11, Operational Test Duration

Item	Failure Type	Test Duration (hours)
One subsystem, a group of subsystems, or a single string SK, Note 1.	Design	500
	Workmanship	
	Random. Note 3.	
Integrated System if integration done after subsystem testing completed. Note 2	Workmanship	200
	Design	
Total Test Time	**Worst Case.** Note 4	700
	Normal. Note 4	500

Note 1, The total test time needed for each subsystems individual or integrated together is 500 hours. This test time can be accumulated during various engineering evaluation or environmental tests.

Note 2. The additional test time at the integrated system level is needed to improve the system reliability regarding workmanship or design (compatibility) defects that could be introduced during the integration or be a result of the subsystem interaction.

Note 3. Correction of random failures assumes system improvement (i, c. a better quality or higher rated component, design improvement, fault protection). Replacement of the failed component dots not guarantee elimination of a future failure of the same component.

Note 4, If the S/C system is integrated after the completion of accumulated 500 hours test of individual subsystems or subsystem groups, then the additional system level testing of 200 hours is needed to eliminate possible design/compatibility or newly introduced workmanship problems. If the integration is done at the latest after 300 hours were accumulated on the subsystems, then there is no need for the additional system level testing. The total time needed for operational testing is 500 hours, resulting in cost savings.

For cost savings, a more aggressive failure investigation and corrective action process can be organized, achieving an industry high reliability growth rate of $\alpha = 0.65$, or a higher test acceleration.

To determine the test duration that is going to be applied in a program or to adjust the efficiency of the failure corrective action system, it is necessary to correctly record all the scoreable failures and evaluate reliability growth using a (Duane) simple graphical reliability growth method.

5.0 Conclusions

A carefully designed reliability growth program can be executed at the subsystem level, and the experience can be applied towards the limited time system level tests. This process facilitates failure diagnosis, and also can be initiated long before the system is integrated.

6.0 References

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